MISSILE & SPACE SYSTEMS DIVISION
DOUGLAS AIRCRAFT COMPANY, INC.
SANTA MONICA/CALIFORNIA

Preliminary Design of an Active Coning Damper for the Rebound Spacecraft

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Prepared by:

R. L. JENKS
Space Vehicle Electronics Section

Prepared for the National Aeronautics and Space Administration Under Contract NAS 5-1294

Approved by: D. E. Anderson

D. E. Anderson
Chief, Space Vehicle Electronics Section

Approved by: H. G. Irwin

H. G. Irwin, Chief
Special Space Systems Engineer

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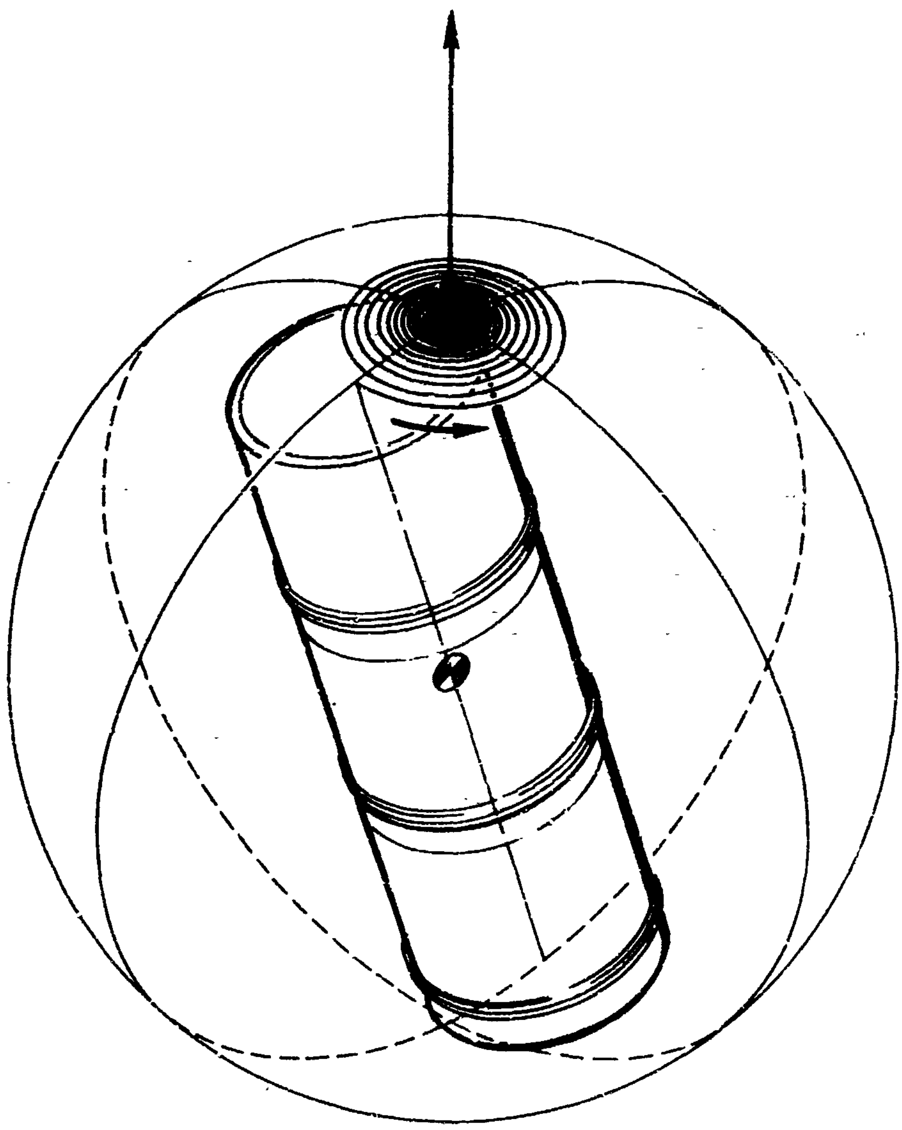
DOUGLAS AIRCRAFT COMPANY, INC.



ABSTRACT

The Rebound spacecraft attitude control is the subject of this report. The method of spin stabilization--as opposed to using the Agena attitude controller--was selected as a more reliable and simple system. Primarily, the report treats the problem of "coning"--i.e., movement in the pitch or yaw axis while spinning in the roll axis--and offers preliminary design data for an active coning damper.

DESCRIPTORS

Coning	Attitude
Damper	Controller
Rebound	Active

FOREWORD

This report, "Preliminary Design of an Active Coning Damper for the Rebound Spacecraft", was prepared by the Douglas Aircraft Company, Inc., Missile and Space Systems Division, as required by the National Aeronautics and Space Administration contract NAS 5-1294.

The author here acknowledges the contributions and suggestions of the following members of the Space Vehicle Electronics Section: Messrs. S. N. Gregg and N. C. Brock in the inverter-controller design; and Messrs. E. B. Moss, K. Shintaku, and C. I. Thornburg in analyzing and designing the damper system. The author also acknowledges Messrs. T. R. Blackburn, D. W. Goldburg, and A. D. Shvetzoff of the Space/Guidance and Control Section; and G. M. Schuetzmann of the Avionics and Guidance Systems Section for vehicle and systems data.

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1. INTRODUCTION

This report discusses the design of an attitude controller for the Rebound spacecraft. This controller must maintain stabilization during the required 40 hour orbital flight period. Two general methods of attitude control—reaction jet and roll spin—will be compared on the basis of simplicity of mechanization. This paper presents a preliminary design of an attitude controller using spin stabilization.

2. REBOUND MISSION

The Rebound vehicle must inject several satellites into spaced intervals along a circular orbit. To do this, the vehicle will enter an elliptical parking orbit which has its apogee at the desired circular orbit altitude. By choosing the proper parking orbit period, the Rebound vehicle will reach satellite injection altitude while previously injected satellites have completed only a portion of their circular orbit. Thus, by releasing satellites at apogee, the Rebound will space them as desired in the circular orbit.

2.1 Vehicle Control

When the Rebound vehicle reaches apogee, two main conditions must be fulfilled before successful injection of a satellite can be made. First, the satellite must be spinning at approximately 120 RPM in order to stabilize it during acceleration into circular orbit. Second, the satellite must be pointed in the proper direction so that its engines' impulse can add velocity in the right direction.

3. USING THE AGENA ATTITUDE CONTROL TO STABILIZE REBOUND

Since the Agena boost vehicle is attitude stabilized, the Rebound vehicle could be left connected after the parking orbit is attained. It would then depend on the Agena vehicle for its stabilization. During flight in the parking orbit, a slow roll-turning rate would maintain an even distribution of sun-heat over the Rebound's surface. At the point of satellite injection, the Rebound vehicle would spin up to the required 120 RPM, inject a spinning satellite, and then de-spin down to the heat-distribution spin rate until the vehicle reached its apogee again. Here, the sequence would be repeated.

4. USING SPIN STABILIZATION FOR REBOUND ATTITUDE CONTROL

By orienting the Rebound's spin axis in the proper direction, spinning the vehicle to the satellite injection spin rate (120 RPM), and detaching the Agena boost vehicle, the required stabilization could be achieved. The satellites would need only to be injected in turn into orbit for the mission to be accomplished.

4.1 Coning Phenomenon

If the vehicle possesses spin about an axis other than its intended spin axis (roll), a wobble will be present. As the vehicle spins, the roll axis will rotate at an angle about the resultant angular momentum axis--describing a "cone". Because the satellite engines thrust vector is in line with the vehicle roll axis, its impulse will be directed away from the desired direction by an angle equal to the coning angle.

4.1.1 Energy States

For a vehicle spinning about its roll axis:

$P_r = I_r \omega_r$ where: P_r = roll angular momentum

$E_r = \frac{1}{2} I_r \omega_r^2$ I_r = roll moment of inertia

ω_r = roll spin rate

E_r = kinetic energy

Spinning about its pitch or yaw axis (assuming $I = I_p = I_y$):

$$P = I\omega$$

$$E = \frac{1}{2} I \omega^2$$

Once the vehicle has been spun and released, its angular momentum cannot change (neglecting gravitational field gradient, etc.)

So, for a vehicle changing its spin axis from roll to pitch:

$$P_r = P$$

and: $\omega = \frac{I_r}{I} \omega_r$

therefore: $E = \frac{1}{2} I \left(\frac{I_r}{I} \omega_r\right)^2$

$$E = \frac{I_r}{I} \cdot \frac{1}{2} I_r \omega_r^2$$

but: $E_r = \frac{1}{2} I_r \omega^2$

so: $E = \frac{I_r}{I} E_r$

The last equation tells us that a vehicle with a given angular momentum will have different kinetic energies of rotation as it spins about axes which have different moments of inertia. Conversely, if the kinetic energy of rotation of a vehicle is changed without changing its angular momentum, it must change its axis of spin to one having the proper moment of inertia.

4.1.2 Rotation of Angular Momentum Vector in Pitch and Yaw Axes

If the angular momentum vector of a spinning vehicle does not lie in the roll axis, then a projection of it must lie in the pitch and yaw plane. (See Figure 1) The rates produced by this projection about the pitch and yaw axes will vary as the projection rotates about the roll axis. Thus, when the projection lies along the pitch axis, $P_p = P_r \tan \theta$ and when the projection has moved through 180°, $P_p = P_r \tan \theta$. By producing a reciprocating torque on the vehicle frame that is in opposition to the projection of the total angular momentum vector on the pitch axis, the projection can be driven toward zero.

4.1.3 Energy Loss Considerations

Kinetic energy loss in the vehicle frame, because of body flexing which creates heat, is expected to be minimal when the coning angle is near zero or ninety degrees (full tumble). Therefore, as long as the tip-off impulse is small at separation from the boost vehicle and energy is supplied to the vehicle before the coning angle is allowed to grow, undue energy loss from body flexing can be avoided. For small coning angles, the angle will grow by the relation:

$\theta = \theta_o \, e^{kt}$ where: θ is the initial (tip-off) angle. *

$E = \frac{I_r}{I} E_r$ is a special case of the relation:

$$E = - \frac{P^2}{2I} \left[\frac{I}{I_r} - 1 \right] \sin^2 \theta$$

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*Thompson, W.T., and Reiter, G.S., "Attitude Drift of Space Vehicles", Journal of Astronautical Sciences, Vol. 7, No. 2, Summer 1960, pp. 29-34.

ANGULAR MOMENTUM RELATIONSHIPS

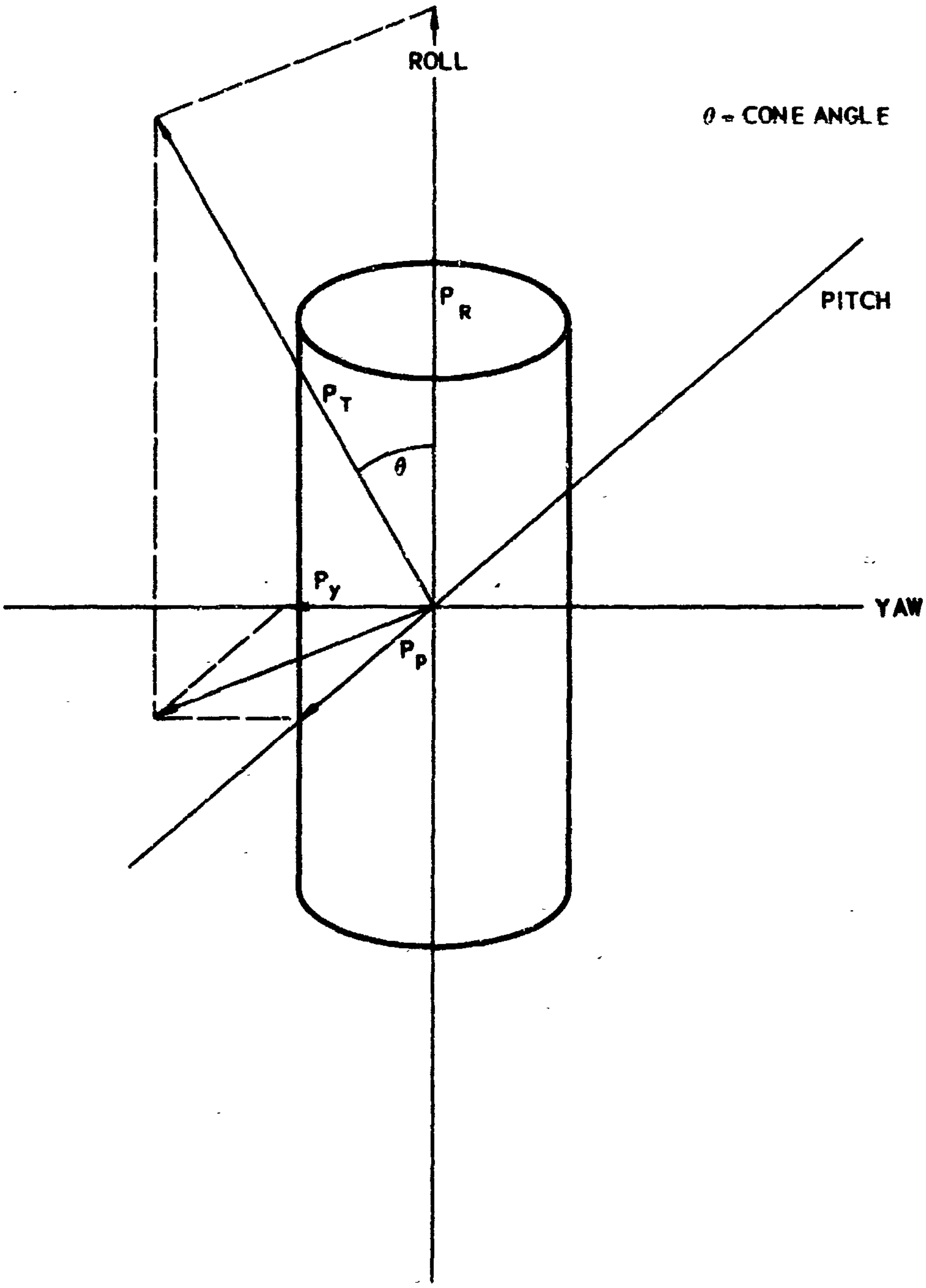


FIGURE 1

so: $$\frac{dE}{dt} = -\frac{P^2}{2I}\left[\frac{I}{I_r} - 1\right] \sin 2\theta \frac{d\theta}{dt}$$

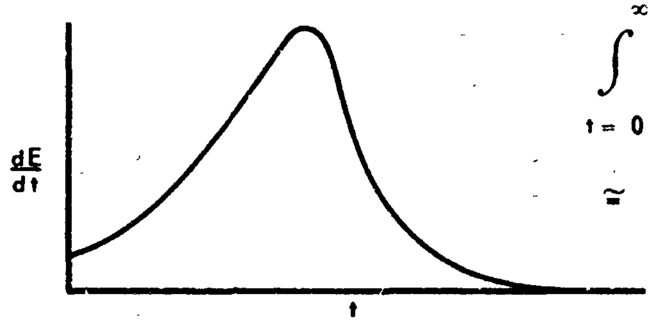
but: $$\frac{d\theta}{dt} = k\theta_o \; e^{kt}$$

so: $$\frac{dE}{dt} = \frac{-kP\theta_o}{2I} e^{kt} \left[\frac{I}{I_r} - 1\right] \sin 2\theta_o \, e^{kt}$$

or: $$\frac{dE}{dt} = k_1 e^{kt} \sin k_2 e^{kt}$$

This is for small angles and I is greater than I_r (a long vehicle).

Power loss near ninety degrees also decreases toward zero because the minimum energy the vehicle can possess is that which is required to maintain its angular momentum about its axis of greatest moment of inertia. So $\frac{dE}{dt}$ will decrease to zero as "t" goes to infinity. The integral of $\frac{dE}{dt}$ from zero to infinity will be equal to the total energy change of the vehicle from tip-off angle to full tumble or for uncorrected coning:



$$\int_{t=0}^{\infty} \frac{dE}{dt} \simeq E_r \left(1 - \frac{I_r}{I}\right)$$

assuming θ_o to be near zero.

4.2 Reduction of Coning Angle

As hinted in paragraph 4.1.2, coning can be curtailed by reducing the magnitude of the projection of the total angular momentum vector on the pitch and yaw plane. Since the projection is rotating in that plane, it is reciprocating on the pitch and yaw axes, and a device which will produce an opposing angular momentum about one of those axes will reduce its magnitude. Although a net angular momentum change cannot be produced within a closed body, i.e. the vehicle, a reciprocating change can be produced alternately storing and releasing angular momentum from some member within the vehicle. As the projection on the pitch and yaw plane is reduced, conservation of angular momentum demands that the removed momentum appear about the roll axis and, consequently, the vehicle goes into a higher energy state.

4.3 Comparison of Stabilization Methods

Table I presents a comparison between the sequence of events that will occur after boost using (1) the boost vehicle control system, and (2) Rebound spin stabilization.

The coning damper will be active after boost vehicle separation and during satellite injections for a total estimated time of one hour. Because the loss of energy from the vehicle frame is small when the coning angle is small, intermittent operation of the damper (estimated 10% duty cycle) will keep the coning angle below the threshold value. The eliminated operations include:

two spin-up operations

two de-spin operations

TABLE OF EVENTS AFTER BOOST

TABLE I

(1) BOOST VEHICLE STABILIZATION			(2) SPIN STABILIZATION		
NO	EVENT	EQUIPMENT	NO	EVENT	EQUIPMENT
1.	ENGINE CUT-OFF	BOOST VEHICLE	1.	ENGINE CUT-OFF	BOOST VEHICLE
2.	COAST ATTITUDE CONTROL / CHANGE ATTITUDE TO INJECTION POSITION	ATTITUDE CONTROL SYSTEM (BOOST VEHICLE)	2.	COAST ATTITUDE CONTROL CHANGE ATTITUDE TO INJECTION POSITION	ATTITUDE CONTROL SYSTEM (BOOST VEHICLE)
3.	ROTATE VEHICLE SLOWLY FOR EVEN HEATING	REBOUND ELECTRIC MOTOR DRIVE ≈ 0.5 RPM	3.	SPIN UP REBOUND	SOLID PROPELLANT SPIN MOTORS
			4.	SEPARATE REBOUND FROM BOOST VEHICLE	PYROTECHNICS & SEPARATION SPRINGS
4, 7, 10	SPIN-UP REBOUND	SOLID PROPELLANT SPIN MOTORS	5	REDUCE CONING ANGLE	REBOUND CONING DAMPER
5, 8, 11	INJECT SATELLITE	PYROTECNICS & SEPARATION SPRINGS	6, 7, 8	INJECT SATELLITE	PYROTECNICS & SEPARATION SPRINGS
6, 9	DESPIN REBOUND	YO-YO WEIGHTS			
	ELEVEN OPERATIONS			EIGHT OPERATIONS	

continuous rotation of the vehicle by electric motor

continuous operation of the boost vehicle attitude control system

The added operations include:

one separation operation

intermittent coning damper operation

The system simplifications resulting from the use of the coning damper will enhance reliability by a respectable margin.

5. THE REBOUND CONING DAMPER

5.1 Operational Requirements

The following operational requirements must be fulfilled by a coning damper system. It must be capable of reducing any initial coning angle to near zero in a reasonable length of time. These three values are here taken to be:

expected initial angle	=	1°
"near zero" null response	=	0.1°
"reasonable time" - response	=	30 minutes

The size of the device is not critical--provided there is room for it in the airframe--and therefore was not considered in this study. The weight of the damper must be held to a minimum. A reasonable design goal will be thirty pounds. Power requirements are directly tied to the weight of the system. With the above weight goal, the power consumption design goal will be 15 watts. The choice of simple design plus qualified and tested components will enhance the reliability of the system. Another advantageous factor will be its isolation from the other Rebound vehicle systems.

5.2 Environmental Requirements

The system will be called on to withstand a variety of environments. It must be fully tested and qualified.

The main preflight environmental stresses which the coning damper must withstand are the following:

Temperature:	-10°F to +125°F
Pressure:	1 atm to 87 mm Hg
Humidity:	per MIL-E-5272C Procedure 1

Launch environmental requirements are:

Temperature:	75°F ± 15°	
Pressure:	1 atm	
Vibration:	8-200 cps	2.7g (zero to peak)
	200-300 cps	4.5g (zero to peak)
	300-2000 cps	9.0g (zero to peak)
Acceleration:	11.25g	

Orbital environmental requirements are:

Temperature:	75°F ± 15°
Altitude:	1500 naut. miles
Test Pressure:	10^{-6} mm of Hg
Acceleration:	0 g
Radiation:	250 RADS, high energy protons

5.3 System Description

The coning damper system must perform in this manner: it will sense any angular rate about the vehicle's pitch axis. It will then produce a torque in the proper phase which will act to reduce that angular rate. Figures 2 and 3 present alternate block diagrams--either using a DC

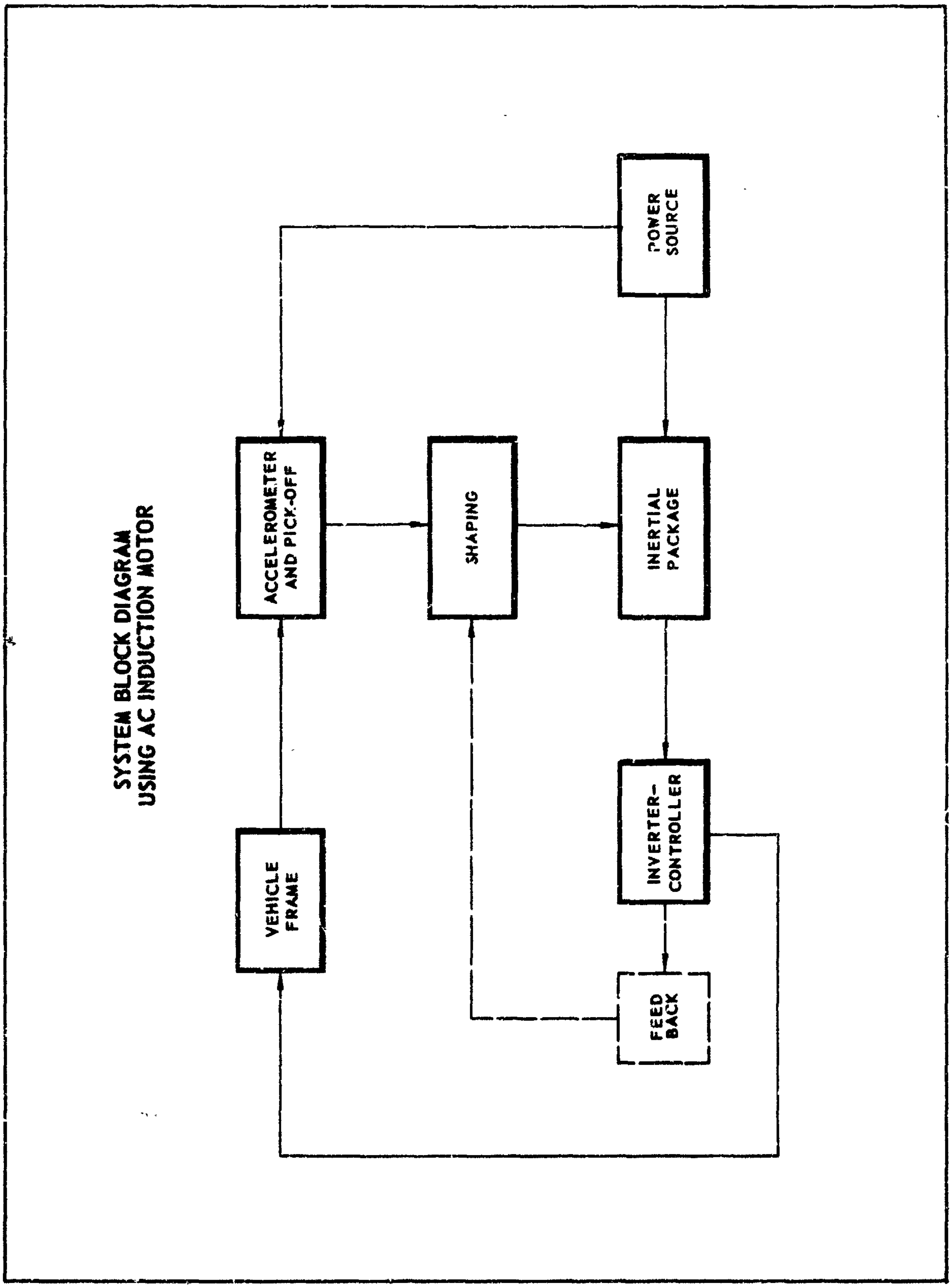

SYSTEM BLOCK DIAGRAM
USING AC INDUCTION MOTOR
ACCELEROMETER AND PICK-OFF
SHAPING
INERTIAL PACKAGE
POWER SOURCE
VEHICLE FRAME
INVERTER-CONTROLLER
FEED BACK

FIGURE 2

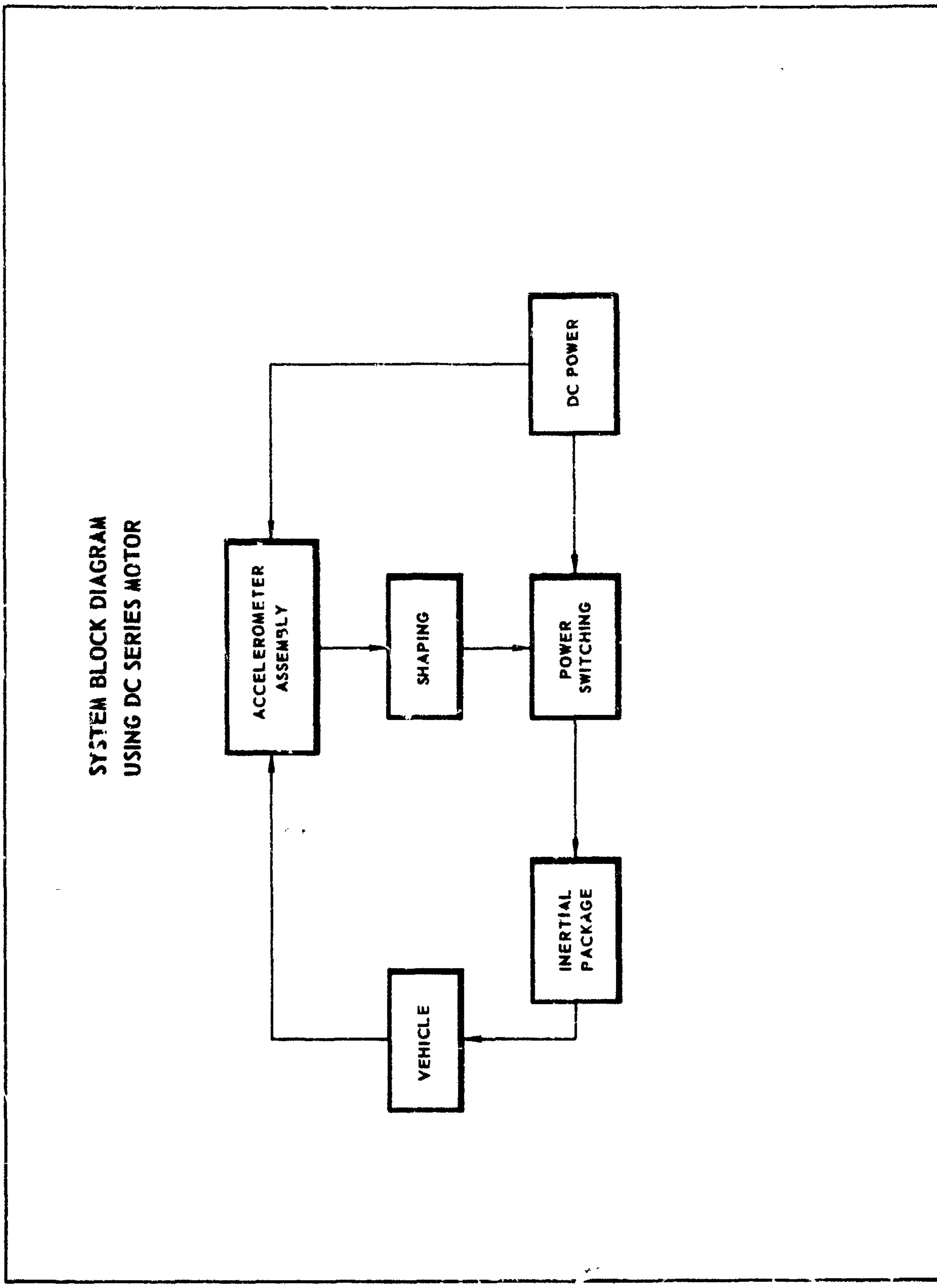

SYSTEM BLOCK DIAGRAM
USING DC SERIES MOTOR
DC POWER
ACCELEROMETER ASSEMBLY
SHAPING
POWER SWITCHING
INERTIAL PACKAGE
VEHICLE

FIGURE 3

power source or an AC power source--of the Rebound coning damper system.

5.3.1 Accelerometer

The accelerometer must respond to fairly low level signals. The peak acceleration (A_p) that it sees in each cycle equals $2 \frac{I_r}{I_p} r_3 \omega_r^2 \theta$

where r_3 is the distance from the center of vehicle to the accelerometer (i.e., two feet).

$$A_p = (2.392) \text{ft/sec}^2 \qquad (\text{with } \theta \text{ in degrees})$$

At tip-off, the accelerometer must respond to a peak-signal of $2.392 \times 1 = 2.392$ ft/sec^2. At null: $2.392 \times 0.1 = 0.2392$ ft/sec^2.

To keep power consumption in the accelerometer assembly at a minimum, a device using a seismic mass with a potentiometer pickoff would be desirable for this application. However, the friction of a wiper arm would keep such an accelerometer from responding at the lower levels that will be encountered. A force balance servo-accelerometer, with slightly higher power consumption, will respond to the minimum acceleration encountered.

5.3.2 Shaping Networks

Both a high pass and low pass filter will be needed in this system. The high pass filter will remove any DC bias caused by accelerometer misalignment and shift of the center of gravity. It must pass signals at one cps or higher. The low pass filter will be a conventional RC shaping network used for system stability.

5.3.3 Inverter-Controller

The inverter-controller will convert battery current to two-phase alternating current. It will supply the alternating current--in correct phase--to the inertial drive motor. For maximum efficiency, it will operate "class D" varying the width of the output current in response to the control signal. Figure 4 shows the output versus input signal of the inverter-controller. The unit will be designed to draw a minimum of current when no power is being supplied to the inertial drive motor.

5.3.4 DC Power Switching

Using a DC inertial drive motor, a power switching device can be made to operate very efficiently. It will switch on power to the motor when the control signal rises above its threshold value and reverse polarity when the control signal voltage goes through zero.

5.3.5 Inertial Package

A design was first attempted which included an induction drive motor and inertial wheel as an integral package. This package would have had the two great advantages of having been already designed and of not having coupling losses between the drive motor and the driven wheel. Subsequent analysis of the vehicle response by analog computer showed that response time was excessive in the torque range for which these packages have been designed. Therefore, a series-DC motor capable of far greater torque has been selected for use in the integral package rather than the induction motor. A typical unit of this type, manufactured by Bendix Company, is illustrated in Figure 5. The inertial package will attach to the vehicle frame and use it as a heat sink.

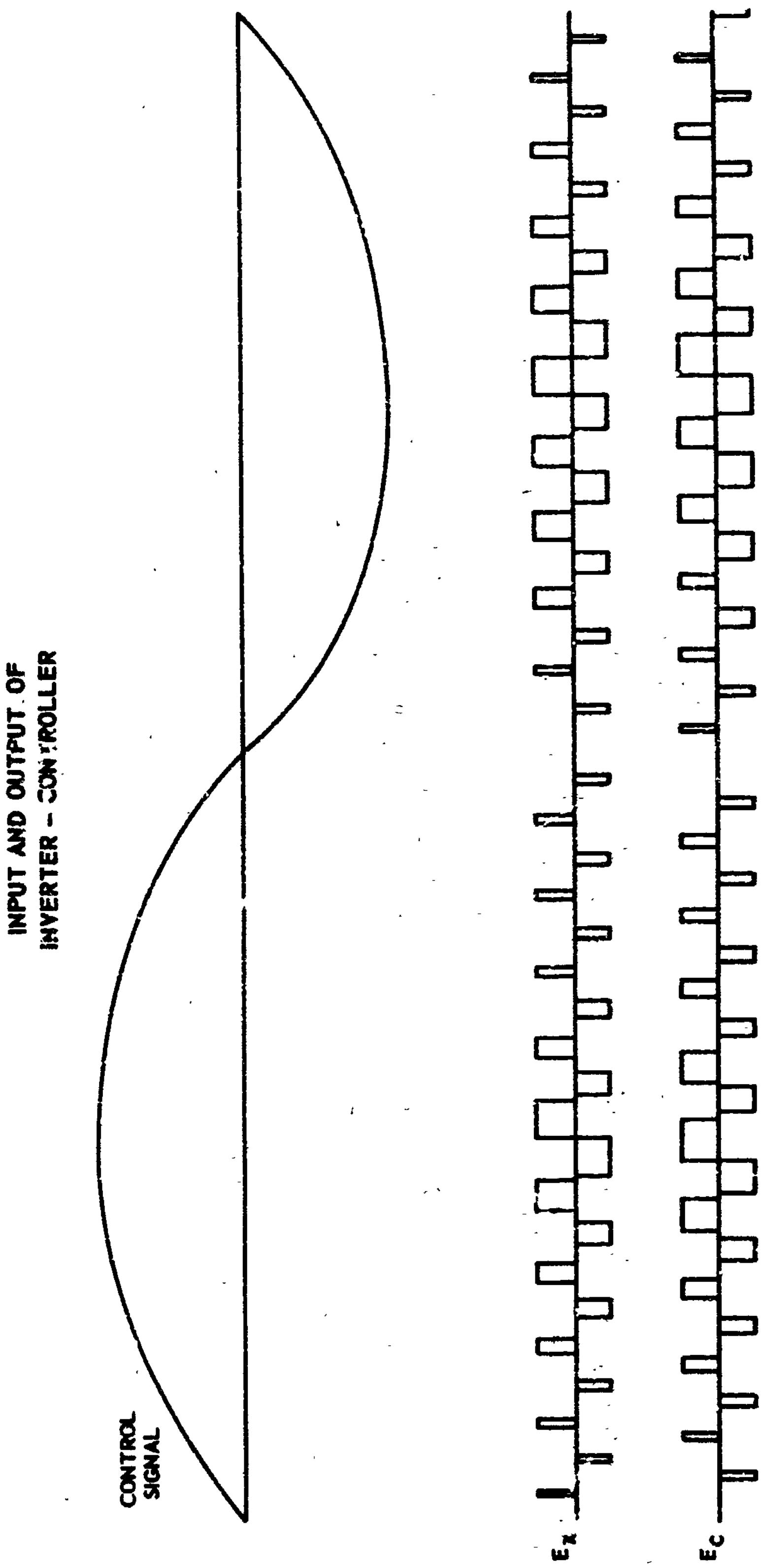

INPUT AND OUTPUT OF
INVERTER – CONTROLLER
CONTROL
SIGNAL
E_x
E_c

FIGURE 4

CROSS-SECTION OF TYPICAL
INERTIAL PACKAGE

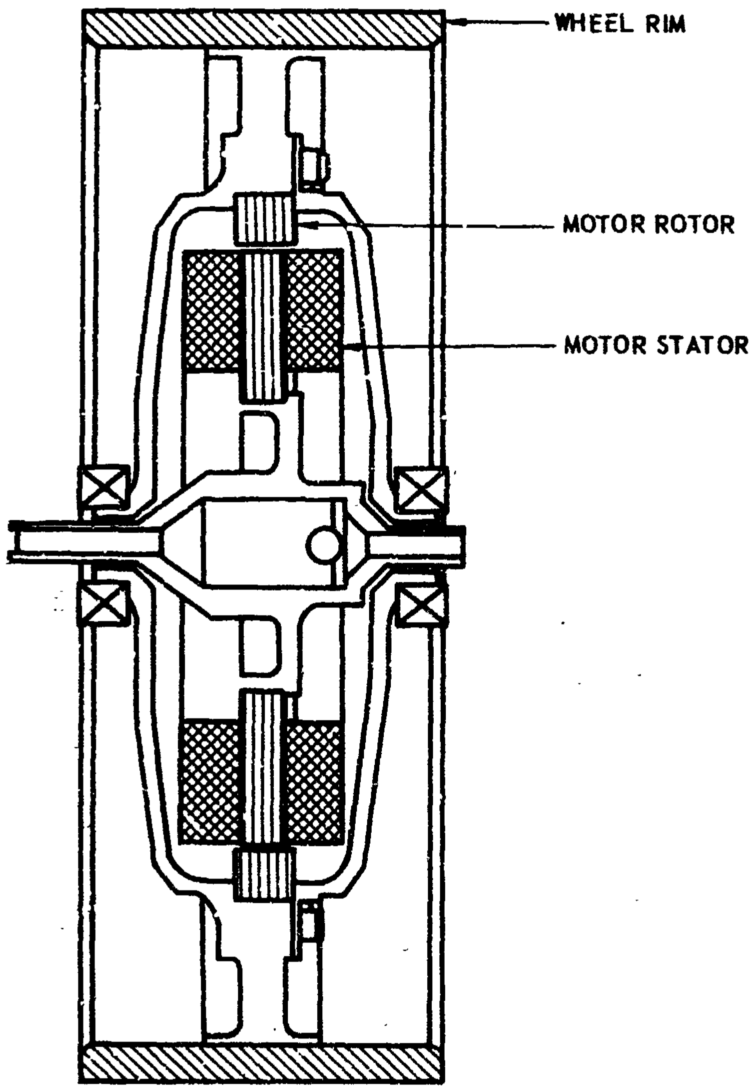


FIGURE 5

A bridge diode circuit will reverse the relative directions of current in the rotor and stator when polarity to the motor is reversed, enabling motor direction reversal to take place.

A saving in current required for the motor could be made by inserting a gear train between the driving member and the inertial wheel, thus increasing the torque on the wheel for a given motor torque. However, because of the simplicity of this integral package, and because it has already been developed for space applications, it has been selected—rather than a gear train drive—for this design.

5.3.6 Feedback

System analysis indicates that feedback will not be required for stability. For simplicity, it would be desirable to avoid feedback altogether. Using some designs, wheel runaway due to accelerometer or amplifier unbalance would require that some rate feedback be used to hold the wheel speed to a limiting value. But with the present design, the wheel speed curve will remain fairly symmetrical about zero and quickly drop to zero when control goes below threshold.

5.4 System Design Considerations

The subsystems of the coning damper consist of the accelerometer assembly, the shaping networks, the power switching, the inertial package, and the power source. This attitude control system has been designed to operate solely on 28 volts DC supplied by a standard space vehicle battery.

5.4.1 Accelerometer Assembly

The accelerometer must respond to an approximate sine wave of about 1.5 cps with a maximum amplitude at tip-off of 2.4 ft/sec^2 and a maximum amplitude at system threshold of 0.24 ft/sec^2. Accuracy, linearity, zero output, and temperature sensitivity are not critical. Resolution and power consumption are critical. A force-balance servo-accelerometer has the characteristics needed. The important parameters are:

Input Power:	less than one watt
Output:	$\pm$ DC voltage
Range:	greater than $\pm$ 0.07475 g
Resolution:	better than 0.001 g
Pressure:	vacuum to one atmosphere

A representative accelerometer which meets these requirements is the DONNER 4310 linear servo-accelerometer. It exhibits the following characteristics:

Input Power:	0.3 watts maximum
Output:	$\pm$ 7.5 volts DC at 1.5 ma
Range:	$\pm$ 1/2 g
Resolution:	0.0001% of full scale
Pressure:	vacuum to five atmospheres absolute
Temperature:	
(storage)	-65°F to $+200^{\circ}$F
(operating)	-40°F to $+200^{\circ}$F

5.4.2 Shaping Networks

Provided the control signal input impedance of the power switching system is sufficiently high, the high pass filter, used for blocking any DC bias from the accelerometer, will present no unusual problems in design. And, standard parts can be used throughout. The control signal shaping network will be a standard RC filter. Together, these two filters can be mounted within the inverter-controller.

5.4.3 Inverter-Controller

A block diagram of the inverter-controller is shown in Figure 6. Essentially, the inverter-controller is a two-phase, "class D" static inverter with pulse duration controlled by the control signal instead of a voltage regulator circuit. The phase-shift network advances or retards the oscillator phase by 90° depending on the control signal polarity. The driver-modulator fires at different levels on the triangular wave from the integrator depending on the control signal voltage. As the control signal voltage drops toward zero, the widths of the output pulses narrow. When the control signal drops below the threshold value, the pulse width becomes zero and no battery power is drawn for the motor. The design is straightforward, involving standard circuits and components. The inverter-controller can be designed to have the following characteristics:

Input:	28 V DC
Output:	2-phase, 4 wire, $\pm$ 90° phase angle (depending on polarity of control signal)
Efficiency:	60%
Quiescent Power:	5 Watts
Weight:	less than 10 pounds

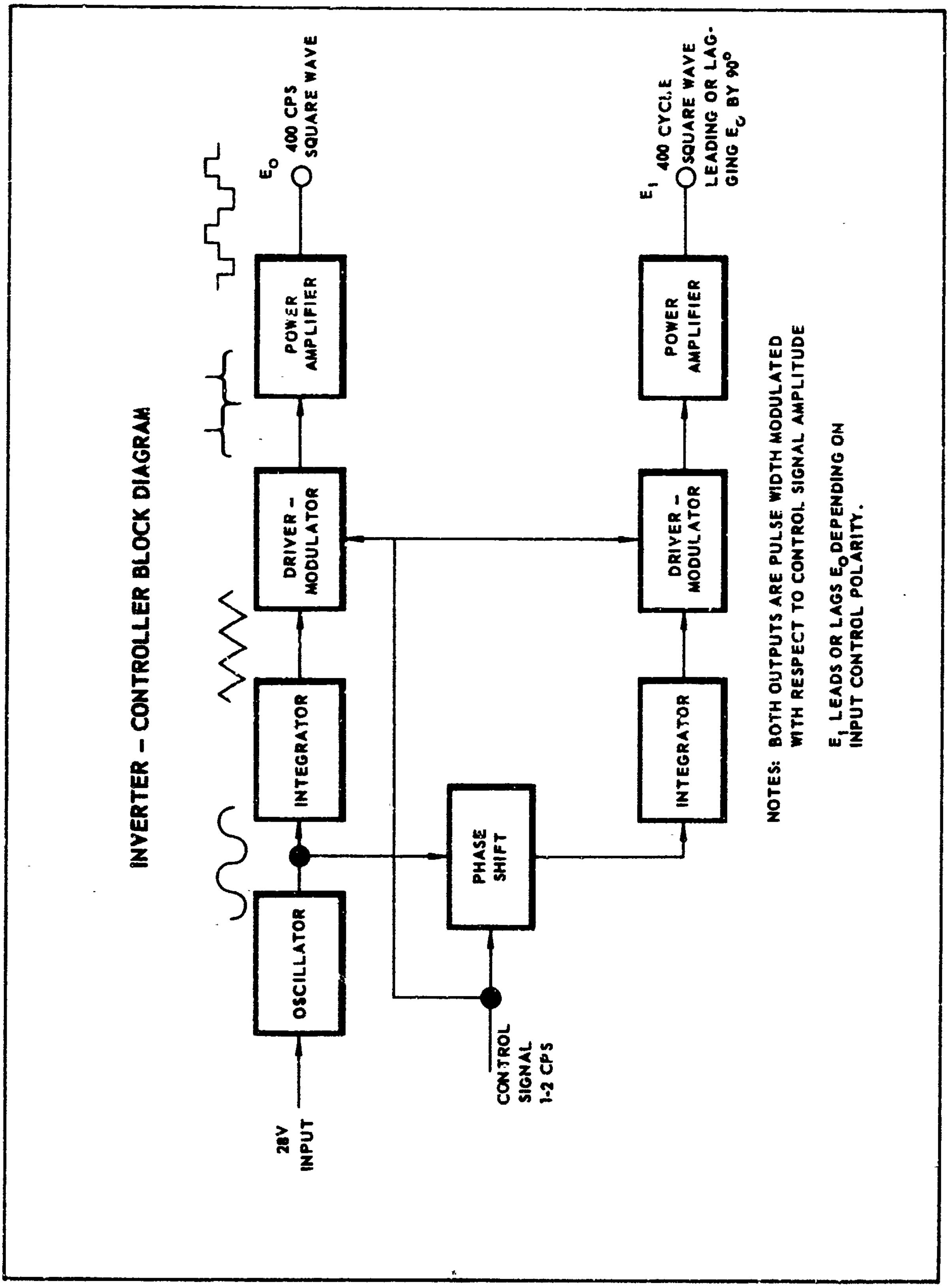

INVERTER – CONTROLLER BLOCK DIAGRAM
28V INPUT
OSCILLATOR
INTEGRATOR
DRIVER – MODULATOR
POWER AMPLIFIER
E_O
400 CPS SQUARE WAVE
PHASE SHIFT
CONTROL SIGNAL 1-2 CPS
INTEGRATOR
DRIVER – MODULATOR
POWER AMPLIFIER
E_1
400 CYCLE SQUARE WAVE LEADING OR LAGGING E_O BY 90°
NOTES: BOTH OUTPUTS ARE PULSE WIDTH MODULATED WITH RESPECT TO CONTROL SIGNAL AMPLITUDE
E_1 LEADS OR LAGS E_O DEPENDING ON INPUT CONTROL POLARITY.

FIGURE 6

5.4.4 DC Switching

A block diagram of the DC Switching device is shown in Figure 7. It will have the following characteristics:

Input:	28 volts DC
Output:	28 volts DC (polarity reversal)
Efficiency:	90%
Quiescent power:	1 watt
Weight:	3 pounds

5.4.5 Inertial Package

The inertial package consists of the drive motor and inertial wheel. The motor has an "inside-out" construction which permits the inertial wheel to be made an integral part of the motor. The unit is sealed, it can operate in hard vacuum, and it has redundant brushes to ensure reliability. It is very similar to units developed for such space vehicles as "Nimbus", "Advent", and "OAO". It utilizes the vehicle frame as a heat sink to remove excess heat. Its characteristics are:

Power consumption:	60 watts maximum
Weight:	18 pounds
Size:	2" outside diameter 4.75" wide
Motor type:	DC series
Input power:	28 volts DC
Inertia:	0.059 slug ft^2
Torque (stall):	1 foot pound

The Bendix Eclipse-Pioneer (X-1790091-1) inertial package stands as an example.

DC SWITCHING DEVICE BLOCK DIAGRAM

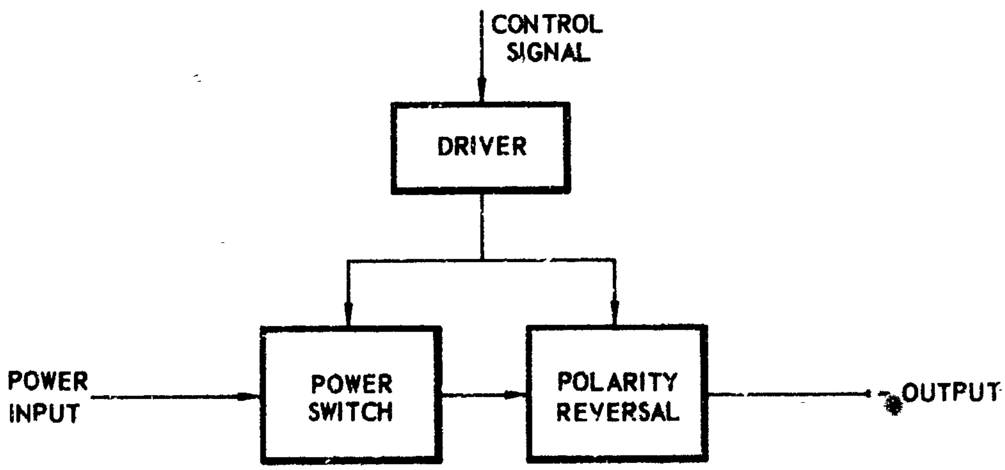


FIGURE 7

5.4.6 Running Time

An estimate of system running time based on vehicle response studies is: one-half hour after boost and fifteen minutes after each canister separation to reduce tip-off coning, and 10% of the coasting time to reduce vehicle frame energy-loss coning. Expected "on time" of the attitude control system would therefore be 0.1 x 40 + 1 = 5 hours.

$$\text{Total energy (on)} = \frac{60}{0.90} \times 5 = 333 \text{ watt hours}$$

$$\text{Total energy (off)} = (1 + 1)\ 40 = \underline{80} \text{ watt hours}$$

(acceleration + quiescent) 413 watt hours total

Choosing a standard HR-15 battery with 17 cells and 420 watt hours, the battery weight will be 14 pounds.

5.5 Overall Performance

The coning damper described in this report can be expected to maintain the alignment of the Rebound vehicle's spin axis with its total angular momentum vector, thus enabling the vehicle to inject its payload accurately into orbit. As mentioned previously, the power required by the coning damper is expected to be two watts continuously throughout the flight and 66.7 watts intermittently for five hours. The subsystem weights are estimated to be:

Accelerometer Assembly	0.5 pounds
Shaping and DC Switching	3 pounds
Inertial Package	18 pounds
Battery	14 pounds
	35.5 pounds total

The coning damper will be designed to reduce the coning angle to less than 0.1 degree. Because of the simplicity of this system and the use of conventional components and designs, its reliability is expected to be better than 0.999.

6. CONCLUSION

The attitude of the Rebound vehicle can be simply and reliably stabilized by the use of a coning damper. Not only is the damper itself quite simple in design, but its use will materially simplify the mission sequence of events.